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Monitoring Water Quality by Remote Sensing

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Preface

The California Department of Water Resources in cooperation with the Stanford Research Institute conducted a limited study to determine the applicability of remote sensing for evaluating water quality conditions in the San Francisco Bay and Delta.

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INTRODUCTION

This is the final report for Landsat follow-on investigation #2319B. The study was conducted by the California Department of Water Resources (DWR) during the period June 1975 through December 1976. The overall objective of the study was to determine if remote sensing could be used to monitor water quality conditions in two areas of California, specifically Lake Tahoe and the San Francisco Bay-Delta. This final report summarizes the major findings, and points out any problem areas encountered during the study period.

The objective of the investigation has been stated earlier. The specific tasks outlined to accomplish this objective are outlined below:

1. Collect and summarize existing ground truth for selected test sites.
2. Collect ground truth data coincident with Landsat and aircraft flights to establish a data comparison base line.
3. Examine selected frames of each type of imagery using manual techniques to identify suspect water quality anomalies.
4. Following initial screening, DWR in cooperation with the State Water Resources Control Board (SWRCB), and the subcontractor Stanford Research Institute (SRI) will initiate comparative analyses among data from each mode of remotely sensed data.
5. Selected imagery from each mode will be enhanced by SRI through the use of the Electronic Satellite Image Analyzer Console (ESIAC). Data products to be prepared with the aid of ESIAC will include:

- a. Numerical tabulation of areas showing visible changes attributable to the pollution source. Estimates of possible error will accompany these area figures.
 - b. Annotated photographs of selected CRT displays. Examples are:
 - 1) Binary thematic masks showing distribution of affected areas.
 - 2) Radiance versus distance profiles for all MSS bands.
 - 3) Composite images showing original data overlaid with thematic masks.
 - 4) 2x2 inch color slides from the color TV display.
 - 5) Time-lapse movies for analysis and technical presentations.
 - c. Written summaries of unusual features noted and of experiences pointing toward promising new processing techniques.
6. DWR and SRI shall jointly develop a data analysis summary matrix which will include:
 - a. Listing of classes of water resources problems.
 - b. For each problem, a rating recommendation for the most suitable photography, imagery (remote sensing system), and spectral enhancement.
 7. For optimal combinations apparent in the matrix, an assessment will be made of the feasibility of electronic data processing for storage and retrieval of the water resources surveillance imagery.

The above list of tasks will be referenced later when discussing the results of the investigation.

STUDY AREAS

The Lake Tahoe and San Francisco Bay-Delta study areas were selected because of their proximity to Sacramento, the relatively large amount of water quality data available, and the presence of known or suspected water quality problems. A brief description of each study area may facilitate understanding the study results.

San Francisco Bay and Delta

The San Francisco Bay and Delta form a complex estuary at the confluence of the Sacramento and San Joaquin Rivers. It is convenient to subdivide this area into two components; the San Francisco Bay and the Sacramento-San Joaquin Delta (see Figure I). The division is partly based on salinity (Delta waters are generally suitable for agricultural, municipal, and industrial uses) and partly as an administrative expedient (separate regional water quality control boards administer the Bay and Delta).

Water quality conditions in the Bay-Delta are influenced by several man-caused factors. First, the Delta is a transfer point where water from the north (from the Sacramento, Trinity, and Feather River systems) is diverted to the San Joaquin Valley and Southern California by State and federal water projects. Water quality in the estuary is affected by freshwater outflow which, in turn, is affected by diversion as well as precipitation patterns. Outflows now vary from less than 4,000 cubic feet per second (cfs) during the late summer to more than 50,000 cfs during peak spring snow-melt.

In addition to freshwater inflow there is sea water moving in and out by tidal action. The combination of fresh and salt water movement results in much of the estuary being fairly well mixed, although recent data (Arthur, 1975) have demonstrated some layering caused by different densities of the two water masses. South San Francisco Bay is relatively stagnant and is only well mixed during peak spring outflows (Conomos, 1975). There is a considerable amount of waste discharged to the Bay-Delta including agricultural, municipal, and industrial. In 1965 there were more than 5 million people living in counties adjacent to the Bay-Delta (Kaiser Engineers, 1969). In this same report it was estimated that approximately 190,000 acre-feet (about 6×10^{10} gallons) of municipal and industrial waste water, and over 2 million acre-feet (6×10^{11} gallons) of agricultural return flows enter the Bay-Delta annually, either as direct discharge, or by way of the Sacramento, San Joaquin and other stream systems.

Kaiser Engineers listed present and potential water quality problems in the Bay and Delta. Their areas of concern were:

1. Delta -

- a. Salinity - Increased water diversion may allow salt water to intrude further into the Delta, degrading the Delta water to a point where it would not be available for present municipal, industrial, and agricultural uses.
- b. Dissolved oxygen - There are periodic low oxygen concentrations in portions of the Delta, generally in the fall when canneries are discharging their peak flows.

- c. Nutrients and algal problems - There are algal blooms in portions of the Delta, and the estimated increase nutrient loading (mainly from agriculture waste) may cause more algal problems.
- d. Fishery problems - Mainly resulting from diversions which cause reverse flows in the Delta (water is drawn across the Delta to the pumping plants and this complicates the normal seaward stream flow) and pump young fish down the canals.

2. San Francisco Bay

- a. Dissolved Oxygen - Some dissolved oxygen problems exist in South San Francisco Bay, although their extent has decreased during the past few years due to upgraded treatment of municipal wastes.
- b. Algae and Nutrients - The algal problem is manifested by dying seaweeds on some beaches around the Bay. Algal problems are not as apparent as in the Delta.
- c. Toxicants - There is some indication that toxic materials contained in discharged wastes are affecting biological communities in the Bay-Delta. These effects may be chronic (long term) rather than acute.
- d. Coliform bacteria - Coliform bacteria levels in the Bay are generally higher than State bacteriological standards for ocean water contact sports. A once flourishing shellfish industry has been shutdown because of excessively high bacterial counts in the clams and oysters. Recent upgraded waste treatment resulting from the 1972 Water Quality Act has probably reduced the shellfish contamination problem.

As is apparent from the above discussion, a study of the water quality of the San Francisco Bay and Delta is no simple matter. There are more than 1,500 square miles of water surface in the system (approximately 435 square miles in the Bay and 1,100 in the Delta) which creates logistical problems when collecting ground truth data.

Lake Tahoe

In terms of water quality, Lake Tahoe is at the opposite end of the spectrum from the San Francisco Bay and Delta. The lake water is of excellent mineral quality and its clarity is among the greatest known in the world. A small (20 centimeter) white disk, the secchi disk, can be seen at a depth of about 100 feet, as compared to 1 to 10 feet in the Bay-Delta. Water quality is a comparative thing, however, and in the case of Lake Tahoe, any decline from its present high quality is not desirable.

The major factor responsible for Lake Tahoe's exceptional water quality is the small watershed relative to the volume of the lake. Tahoe is one of the deepest lakes in the world, with a maximum depth of more than 1,500 feet, with an average depth close to 1,000 feet. The total volume of the lake is 122 million acre-feet (3.9×10^{13} gallons), and has an average net inflow of approximately 500,000 acre-feet. Using these rough figures, the theoretical hydraulic residence time (the average time a molecule of water might be expected to remain in the lake, assuming complete mixing) is on the order of 240 years.

In addition to Lake Tahoe's watershed being relatively small, it has historically been low in nutrients; thus the inflowing waters contained few nutrients to enrich the lake. With the coming of large numbers of people

to the Tahoe basin, first during the gold rush, and later as the region became a center for recreational activities (gambling, skiing, and camping), certain cultural activities began to affect the lake. The gold miners cut most of the timber for use in the mines, which led to erosion. The later residents in the region discharged sewage to the lake (either directly or through septic tank leachfields), and built roads, houses, and ski areas which led to more erosion.

The overall result of man's activities in the Tahoe Basin has been to slightly enrich the lake, especially the shore areas, by the addition of nutrients contained in sewage and eroded sediments. The major water quality problems are thus algal growth and turbidity. The impact of the problems would not be noticed in most waters of the world but can be significant in such an environmentally sensitive area.

Steps have been taken in the Tahoe Basin to prevent, or at least minimize, the impact of man on the lake. Sewers have been installed around the lake and the sewage is collected and exported from the Basin. Studies are being conducted to determine how best to control erosion (limit building, put cover crops on slopes, etc.). These steps have been fairly successful and in general water quality problems are under control.

The California Drought

Water quantity and water quality are closely interrelated. With substantial flows, potential pollution problems become insignificant because the pollutants are diluted to nonharmful levels. However, in the case of Lake Tahoe, water quality conditions can actually be better during low flow years than in times of plentiful rainfall. With low flows, sediments are not washed into the lake; therefore, turbidity and enrichment problems are minimal.

California (at least the northern part) may be in the beginning of a dry cycle; the past two years have had much lower rainfall than normal. The amount of rainfall in California varies considerably from area to area, and the effect of the drought has also varied; but in many of the watersheds draining to the San Francisco Bay-Delta system, the last two years have seen less than one-half the normal rainfall. The Tahoe Basin has suffered a similar fate.

The dry years have affected water quality, which in turn has affected the conduct of the present study. The largest impact to the study was the decision to withdraw the Tahoe Basin from the study plan because of low flows. This decision was reached for two reasons: (1) turbidity problems (and accompanying nutrient enrichment) were minimal during the entire study period; and (2) there has been considerable work done on Lake Tahoe, in terms of the use of remote sensing, by two organizations, namely the University of California (Davis campus) and the State Water Resources Control Board (in cooperation with the Regional Water Quality Control Board, Lahontan Region, and the California Department of Fish and Game). An analysis of their findings is included in a later section.

Related Studies

A review of pertinent literature is essential to most studies and is especially so in limited studies where constraints of time and money preclude conducting a thorough investigation of all possible aspects of the problem. In this particular instance, the literature review can be particularly valuable because it allows more general conclusions than could be drawn from the study data alone.

Although the field of remote sensing is relatively new, a vast literature exists and an attempt to completely review even that portion dealing with water quality would be overwhelming. This review is limited to those articles readily available and which directly concern the use of remote sensing to monitor water quality conditions. For convenience the articles are divided into three groups:

1) those pertaining directly to the Bay-Delta, 2) those pertaining to the Lake Tahoe area and, 3) articles of describing applications in other areas of the country.

Bay-Delta Studies

Draeger, et al. (1974) reported on the usefulness of remote sensing techniques for the environmental monitoring of the Sacramento-San Joaquin Delta. Their study was conducted under contract to the California Department of Water Resources and involved a limited literature review and an even more limited field investigation. Their report contained the general conclusions that remote sensing had great potential, but in 1974 the state-of-the-art was such that the Department could not obtain the desired quantitative water quality information by means of remote sensing. They did recommend that small format photography from a conventional aircraft could provide useful qualitative data, especially related to gross changes with time.

Chandler, et al. (1970) conducted a study to evaluate the utility of aerial surveillance methods in water quality monitoring. The authors were from the space division of North American Rockwell and the work was for the State Water Resources Control Board. The authors concluded that certain water quality problems (oil spills, thermal anomalies, algae

blooms, turbidity, and color were listed) could be remotely sensed using various parts of the electromagnetic spectrum. The main recommendation from the study was that the State Board should design and fund, with cooperation from NASA, a comprehensive field study to thoroughly evaluate remote sensing. The current study is an outgrowth of this recommendation, only a much more modest scale.

In another State Board study Fraga and Holland (1973) reported on low altitude aerial surveillance for monitoring water quality control activities. The emphasis was on obtaining qualitative enforcement data using 35 mm cameras and low flying aircraft. For example, a dairy might have been ordered to build a pond for containing wash water from the barn. Periodic flights could be used to monitor compliance with this order and also to check on others in the immediate area. There was little or no attempt to obtain quantitative water quality data from these flights. Based mainly on results presented in this report, the State Board (and regional water quality control boards) has initiated a low level (both in altitude and cost) aerial surveillance program. The program serves to point to existing and potential water quality problems which can be investigated in more detail by subsequent site visits.

Carlson, et al. (1975) reported on principal sources and dispersal patterns of suspended particulate matter in nearshore surface waters of the northeast Pacific Ocean, including a section on the San Francisco Bay and Delta. Remote sensing was by satellite (Landsat) and high altitude (U-2) aerial flights. Extensive ground truth data were obtained for the Bay-Delta. Landsat imagery did provide some information as to large-scale circulation patterns in the Bay, but they found that resolution and repetition were at marginal levels for detailed study of small,

rapidly changing features. Conventional aerial photography (especially such sophisticated systems as found on U-2 aircraft) appeared to provide more usable coverage of turbidity patterns (and circulation patterns) in estuarine systems.

Horne and Nonomura (1976) used remote sensing to detect drifting macroalgae in a restricted portion of San Francisco Bay. The information contained in multiband low altitude photographs provided evidence about the drift patterns of the algae and their relative health. The remotely sensed data and surface observations were used to develop means of keeping the algae away from the beach and thus eliminate problems caused by the decomposing algae. The main restriction on the use of remote sensing was the low transparency of the water. Attempts to obtain maximum penetration by photographing only at low sun angles, and low windspeeds (to ensure that suspended sediment concentrations were minimized) were only partially successful because the resulting early morning flights often ran into fog and overcast problems.

Lake Tahoe

Goldman (1974) published the results of an extensive five-year study of the eutrophication of Lake Tahoe, emphasizing water quality. One aspect of this study was an evaluation of the Truckee sediment plume in Lake Tahoe, and its affects on the lake's aquatic environment. A review of this rather complete study can provide insight into the applicability of using remote sensing to assess subtle water quality changes in an ultra-oligotrophic lake.

Four days were selected for Goldman's study: March 29, April 12, June 7, and June 20, 1971. Color photography and multispectral photography from conventional aircraft were used to record the plume. At flight time a field crew in a fast boat made transects across the plume measuring such parameters as light transmission, temperature, Secchi depth, algae and bacterial productivities, algae types, and water chemistry. Data analysis included converting photographs into line drawings based on a subjective (visual) estimate of film densities. Statistical analysis was used to correlate plume density with ground truth measurements.

Analysis of the multispectral photographs indicated that the blue and green bands provided the most plume detail. Results of the correlation analysis demonstrated that certain of the water quality parameters were highly correlated with relative plume density, especially bacterial activity. The authors concluded that the bacteria were probably associated with sediment particles entering the lake.

The high correlation between sediment plume density and bacterial activity was reported to be particularly significant because it provided a mechanism by which organic materials in the sediments were made available for algae growth. Thus, remote sensing provided a rapid and sensitive means for evaluating the importance of sediment as a contributor to the eutrophication of Lake Tahoe.

Other Areas

Rogers, et al. (1975) reported a study of using Landsat-2 data to prepare a water quality map of Saginaw Bay. The authors processed computer compatible tapes by use of a Bendix Multispectral Data Analysis System. Ground truth

data were collected at the time of the satellite overflight and regression equations developed relating water quality parameters to mean reflectance in the four bands. Water quality parameters measured included: temperature, conductivity, chlorides, sodium, Secchi depth, chlorophyll a. Not all of these parameters could be sensed directly but were indirectly sensed because of their association with a particular water mass. In this particular case highly turbid water from the Saginaw River mixing with Lake Huron water provided the contrast needed to define the water masses.

Using only simple linear regression techniques, regression equations were calculated with reflectance (individual band digital counts) as the independent variable and a specific water quality parameter as the dependent variable. For example:

$$\text{Temperature (}^{\circ}\text{C)} = 13.186 + 0.157(\text{Band 5})$$

Regression correlation coefficients ranged from a high of 0.972 (meaning that the equation explained about 95% of the observed variance of the dependent variable) for total phosphorus to a low of 0.459 (only explained about 20 percent) for chlorophyll a. The high correlation for total phosphorus can be easily explained since this element was probably associated with the inflowing sediment. The lack of correlation for chlorophyll a is not as easily explained because chlorophyll should show up quite strongly in at least one of the bands, especially in view of the relatively high concentration (approx. 4 to 70 ug/l) encountered.

One of the problems in the preceding type of analysis is also illustrated by data presented by Rogers et al. (1975). The prediction equation for chlorides is shown to be:

$$\text{Chlorides (mg/l)} = 555.378 + 56.450 (\text{Band 6})$$

With a regression correlation coefficient of 0.829. Looking at the equation one obtains the impression that the distribution of chlorides can be pretty well explained by knowing the reflectance of a Landsat - 2 image. The only problem with this impression is that at least some of the original chloride data were seriously in error. (Many of the chloride values in their Table I were higher than the total dissolved solids, in other words the part was greater than the whole). With the difficulties encountered in obtaining representative samples and correct analytical results, care must be taken to insure that data used in statistical analysis contain a minimum amount of error.

The last example of how remote sensing has been used to assess water quality comes from California in a report by Anderson and Horne (1975). The authors were interested in measuring concentrations of nuisance blue-green algae in five California reservoirs. One of the more significant findings of this study was that blue-green algae, a group which includes the most common nuisance forms in lakes and reservoirs, have a definite spectral signature which can be recognized from an aerial platform. In particular, blue-green algae reflected large quantities of light in the near infrared (700-1050 nanometers) and more overall light per unit of algal biomass than other algae. It appeared that the increased reflectance was caused by the presence of small gas vacuoles in the cells. Gas vacuoles are not found in other algae.

The aerial photographs of algal growth enabled investigators to determine the rate at which the algae drift and where the surface currents are most likely to cause accumulation of algal masses. Through the use of remote sensing the authors were able to position a large scale algal

control project at a location where there was more chance of positive results. For this type of work a sequence of images during the day (and for even longer periods) was needed to detect movement. At one of the lakes (Clear Lake) a novel approach of placing the sensors at the top of a nearby mountain was suggested. The approach was designed to overcome the expense of calling several flights during the week and to provide more complete coverage. Algal blooms can surface and breakup in a matter of a few hours, thus frequent photographs were deemed essential.

There are many other reports which could be cited - reports providing examples of other attempts to use remote sensing for water quality monitoring. In general, however, these reports are concerned with one of two areas of water quality - for example measurement of turbidity patterns or algal distributions, both surface phenomena. Wezernak, Lyzenga, and Polcyn (1974) did use airborne multispectral sensors to determine the distribution of the green alga Cladophora along the shoreline of Lake Ontario. This alga grows attached to the bottom and thus water clarity is important to its growth and to its availability to be sensed. In the case of Lake Ontario, the authors reported the distribution of the algae to depths as great as five meters.

METHODS

The general approach to the study was to obtain Landsat imagery of Lake Tahoe and the San Francisco Bay Delta from the EROS Data Center. Imagery was in the form of positive transparencies in bands 4, 5, 6, and 7. On three of the satellite flight days U-2 flights were scheduled over both areas and a limited amount of ground truth collected. Ground truth data were supplemented by data obtained as the result of other

regularly scheduled monitoring efforts in the area. Data analysis, especially in terms of the images, was done by the Stanford Research Institute on their ESIAC (Electronic Satellite Image Analysis Console). In the next few pages I discuss how each step of the methodology was conducted.

An Imagery Acquisition

A search request was sent to EROS to obtain the required imagery. Since Lake Tahoe was subsequently dropped from the study, only those images concerning the Bay-Delta are discussed in detail. One item about the Tahoe data which could have been important was the way in which the images missed capturing the lake. During the entire study (18 months) only a few photographs of the lake were delivered. Most of the data were from north or east of the target area.

For the San Francisco Bay-Delta we obtained images from 14 dates (from July 75 through June 76) that were considered at least marginally useable. Cloud cover was an important factor limiting the usefulness of the data and many of the images sent contained only portions of the Bay-Delta or often none at all. In the end, however, there were sufficient satellite data on which to make the analysis.

U-2 Imagery Acquisition

Requests for U-2 flights were coordinated through NASA - Ames and the Goddard Space Flight Center. The three flights called were flown on April 29, 1975; September 30, 1975; and June 17, 1976. Although the original plan was to have the U-2 fly the target area during the same time as the satellite this was only accomplished on the second and third flights. A further complication was that the satellite was turned

off during the third flight. Thus, as it turned out, the only flight in which coincident coverage was obtained was on September 30, 1975. During the flight there was a ground truth team on the water, thus making it a successful mission.

On all U-2 flights, coverage was complete and image quality excellent. Dual RC-10 cameras with high definition Aerochrome IR (SO-127) and aerial color (SO-242) films were used to obtain the images. Focal length was normally six inches, although on September 30, 1975, flight 12-inch focal length lenses were used.

Image Handling by Stanford Research Institute

Satellite scenes were sent to Stanford Research Institute where they were screened for aerial coverage and cloud coverage and those found suitable were placed into a 4-band "sandwich". This sandwich was prepared by taping all 4 bands into an envelope in a superimposed position so they could be readily found and viewed. The individual images (each band of each scene) were then entered into ESIAC's storage register.

The ESIAC system has been developed by Stanford Research Institute personnel to analyze data from meteorological and earth resources satellites. The system uses television scanning, storage, editing, and animation techniques to facilitate rapid qualitative and quantitative analysis of data, mainly from satellites, but also from other sources of photographic images.

The satellite images were put in ESIAC's storage by a vidicon camera (item number 4 in Figure 2). Zoom optics and an extensive system of micropositioners permitted scaling of the image and exact registration to scenes or sequences already in memory. Images were stored on an

analog video disc memory, which has a capacity of 600 full TV frames, often handled in pairs to provide 300 bispectral frame pairs. Frames could be assessed sequentially in milliseconds, or randomly in seconds. A fast digital-to-analog interface and cable link to a nearby computer provided a means for loading the disc memory with raw or processed images derived from digital tape. Storage and handling of the images as TV signals permitted quantitative measurements to be made with useful precision at a small fraction of the time and cost required for a fully digital system of comparable versatility. Measurements and logic decisions could be made on radiance data pertaining to any region of the scene while it was being viewed as an image.

After the data were entered, an array of small preview monitors could be used to continuously display selected contents of the storage register. The operator used simple switching and mixing controls to merge imagery from the register into a composite image on the main viewing screen. With ESIAC the potential was there to create a time-lapse display by cycling through the stored image sequences. Photographs of the main display (perhaps with merged or enhanced images) by a movie camera could then be used to make a hard copy of the time-lapse sequence.

A color display was also available to enhance data presentation. In this study colored images were prepared to determine if they provided more information than conventional black and white photographs.

ESIAC had other features which were used in the analysis of the satellite (and U-2 data). An auxiliary overhead vidicon camera fitted with zoom optics was suspended over the horizontal work surface. While it was used for hard copy data entry, its more usual function was to achieve

temporary superposition of maps on the displayed image for orientation. Equally useful was its function in output recording. Line drawings sketched on a notebook page or other paper located on the desktop appear merged with the display image without parallax, and features too subtle to photograph well could be documented by hand drawing directly on the paper.

A 17-inch monochrome display could be connected in parallel with any of the other displays to facilitate photographic data taking. It was also often used to hold a reference picture for side-by-side comparison to other displays.

The operator controlled the position and size of the digitally-derived measuring cursor which could be made to appear in several forms (cross, dot, box, box outline) and was used to measure linear displacements. It was also used to specify individual pixels or rectangular pixel groups within the image for measurement, rerecording, or other special consideration. The cursor location could be intensified on any or all monitors to help in coordinating the displayed data.

A dual-channel oscilloscope was used to display video signal amplitude versus time for various level setting and supervisory needs. When triggered in time coincidence with the cursor, this display could function as a microdensitometer and was used to provide a radiance profile along any specified scan line or portion thereof.

A pen-and-ink plotter was connected to the waveform monitor oscilloscope via a sampling interface unit. It permitted large, sharp, hard copy records to be made of radiance profiles or any other repetitive waveform displayed on the oscilloscope.

Stanford Research Institute personnel attempted to prepare a motion picture using scenes available for a selected portion of the Bay-Delta. All bands were examined, both separately and as false color composites prepared by using combinations of the individual bands for each scene, to determine which final image provided the best definition of feature of interest. Images were projected in either positive or negative polarity.

In Suisan Bay, a region of the Bay-Delta (see Figure 1) in which algal blooms have occurred in the past, five points near existing sampling stations were selected for reflectance profiles. Essentially east-west lines were drawn through these points and reflectance profiles obtained through the use of the oscilloscope and the X-Y plotter. The profiles for September 30 Landsat and U-2 flights were plotted for comparison with visible features on the original images and with available ground truth.

Ground Truth

Ground truth collected in this study was very limited because the small budget did not include enough money for such an expensive activity (about \$1,000 per day for sampling the Bay-Delta). I examined data from other Bay-Delta monitoring programs (Department of Water Resources, U.S. Bureau of Reclamation, and the U.S. Geological Survey; in particular) to obtain supplementary data. Two types of information were obtained: (1) data from samples collected at the approximate date, time, and tidal stage as the overflight data; and (2) information on the long and short term temporal variation of selected water quality parameters. Although such information might not correlate directly with the remotely

sensed images, it would provide a better idea of the applicability of using data that were obtained at relatively infrequent intervals and on an instantaneous basis.

U-2 Data

Incoming U-2 flight data were routinely screened using a portable light table to determine if any gross water quality problem areas were apparent. All three films were also taken to our Red Bluff office for examination on their Vari-Scan System which was recently acquired as surplus from NASA. Vari-Scan amounts to a rather elaborate light table in which magnification, and some manipulation, of the image is possible. These flight films were examined visually, but with a knowledge of potential water quality problem areas (supplied by the Regional Water Quality Control Boards). With such knowledge, more attention was given to those areas where surface anomalies might appear.

RESULTS AND DISCUSSION

The organization of this section does not follow that of the previous chapter on methods. First, the Bay-Delta is characterized from a water quality standpoint, then the imagery is examined to see how well ambient water conditions can be evaluated by image characteristics. Although the entire system is considered in this section much of discussion is particularly concerned with Suisun Bay. As mentioned earlier, the Suisun Bay has a history of algal blooms, features which should be prominent in photograph images. An additional reason for its inclusion is that this area is where the seawater - freshwater, interface occurs and the resulting effect on hydrodynamics and sediment transport appear to make it of primary ecological importance to the entire Bay-Delta

(Arthur, 1975). And anything of such significance to the Bay-Delta is important to California because, as mentioned earlier, the Delta acts as the transfer point for Sacramento River water moving south through the State and Federal Water Projects.

Water Quality Conditions in Suisun Bay

Table 1 lists the dates on which useable satellite data were obtained.

<u>Date</u>	<u>Time</u>	<u>Remarks</u>
4-30-75	17:58:0	
7-3-75	18:11:3	
8-25-75	18:05:0	
9-30-75	18:04:5	
10-19-75	18:10:0	
11-6-75	18:09:0	
11-23-75	18:04:2	
12-12-75	18:09:5	
12-30-75	18:09:1	
1-16-76	18:03:5	Clouds
4-15-76	18:01:2	
5-3-76	18:00:5	
5-21-76	18:00:2	
6-8-76	17:59:3	Clouds
6-26-76	17:59:3	

Table 1. Dates for which satellite imagery covering Suisun Bay is available.

The California Department of Water Resources has four monitoring stations in or near Suisun Bay. They are: D2 (Suisun Bay near Preston Point); D6 (Suisun Bay off Bull's Head Point); D7 (Grizzly Bay); and D8 (Suisun Bay off Middle Point). These stations were sampled on 19 occasions in 1975 and three of these sampling visits fell near or on the day satellite coverage was available. The University of California (Davis Campus) had one station, M7, in Suisun Bay, which was visited eight times during the January-June 1976 period. The U.S. Geological Survey has three stations in the Suisun Bay area which were visited during the same period as the two 1975 dates for which satellite coverage is

available. From these data sources water quality conditions in the area of interest are described in the following paragraphs.

The Suisun Bay region of San Francisco Bay-Delta is quite turbid.

Figure 3 illustrates the variation of secchi depths (the lowest depth at which a 20-cm black and white disk is visible) for two sites within the Bay. Summer-time values are on the order of 10 inches, which means that about 99% of the surface light disappears within the upper 30 to 40 inches of water.

Suisun Bay is moderately rich in phytoplankton (floating algal cells).

Figure 4 contains plots of chlorophyll (an algal pigment) vs. time for the same two sites in the Bay for 1975. Maximum chlorophyll levels were about 30 ug/l, which is indicative of algal bloom conditions.

In clear water chlorophyll levels greater than 25 ug/l can cause aesthetic problems; however, in the turbid waters of the Delta, such concentrations would be barely visible to the unaided eye. The algae in the Delta are diatoms and greens, algae which are less susceptible to remote sensing than blue-green (Anderson and Horne, 1975).

The Suisun Bay portion of the western Delta is strongly influenced by the tidal cycle, which on the west coast consists of two highs and two lows during an approximate 25-hour period. During the cycle surface turbidities, as well as other water quality parameters, undergo almost constant change. An example of the magnitude of this change for two parameters (turbidity and specific conductance) is shown in Figure 5.

These data were obtained on August 17, 1976, by anchoring a boat in the Bay and by means of a continuous analyzer-recorder, monitoring changes in such parameters as dissolved oxygen, temperature, chlorophyll, specific conductance, and turbidity. The values in Figure 5 were picked

TABLE 2 ENHANCEMENT AND RECORDING PROCEDURES EVALUATED
A. COLOR DISPLAYS

<u>METHOD</u>	<u>RESULTS</u>
1. "Conventional" SRI two-primary display. One IR band in Red, one visible band in Cyan.	Good differentiation between water, vegetation, and bare soil themes. Sediment pattern shows no pronounced color contrasts, merely changes in brightness or color "value."
2. Three primary display. Blue = MSS 4 from disc Green = MSS 5 from disc Red = MSS 6 from camera	More colorful, particularly with regard to bluer water. Information content for sediment not noticeably improved over (1). Judged not worthy of the additional set-up time for most applications.
3. Two primary display, with Red and Cyan inputs fed from various combinations of band records, with and without polarity inversion. The objective was to add more pronounced color contrast to the sediment pattern.	A wide variety of colorful displays, but no one procedure evolved that appeared to be universally useful. As a result, interpretation required considerable mental gymnastics. Reference color tablets would be helpful, for detailed study of individual images, but would not be practical for time-lapse presentations. Most effective single procedure was to select the band image evidencing the greatest sediment-water contrast (usually MSS 6) and display it in both polarities, as a positive in Red and as a negative in Cyan. This colored the higher sediment areas red (or at least maroon) in addition to increasing their brightness.
4. Repeat of methods (1) and (3) above but with camera controls adjusted for nonlinear amplitude response. Low radiance regions stretched, high radiance regions compressed.	Some improvement with very careful work, but generally judged to be not worth the effort. Particularly annoying were combinations that resulted in gaudy, unnatural combinations in large quantities, for example from the high IR reflectance of vegetated land areas. In addition to being subjectively distracting these regions tended to cause saturation, blooming, and flare in the display that degraded the image quality in the lower brightness water regions.

ENHANCEMENT AND RECORDING PROCEDURES EVALUATED, CONT'D
B. MONOCHROME DISPLAYS

METHODS

1. "Conventional". Positive display of signal derived from scanning positive transparency of band showing greatest water-sediment contrast. Linear camera response. Display background and gain adjusted for optimum subjective viewing, or at lower overall contrast for best photography.
2. Negative display. Input same as (1) above. Signal inverted just prior to display.
3. Same as (1) and (2) above but with camera controls adjusted for non-linear amplitude response. Low radiance regions stretched, high radiance regions compressed.
4. Input from photographic negative transparencies. Camera signal inverted before recording or display. Linear camera amplifier response.
5. Same as (4) but with non-linear camera amplifier response. Further stretch added to regions of low radiance (in original scene). Severe compression above gray step four.

RESULTS

Baseline. Usually considered marginally adequate.

Power law output/input characteristic of display CRT shifts apparent contrasts in low radiance and high radiance portions of the original scene as well as their absolute brightness in the display. Occasionally effective for sediment plumes, but usually just invites mental hesitation to interpret whether the plume should be bright or dark.

Main effect is to improve the signal-to-noise ratio in the low radiance regions for signals recorded on disc. Some improvement in overall image quality both for viewing and photography.

Best scheme found for direct CRT viewing of December 30, 1975 image, but photographs were judged inferior to those of method (1) above.

ENHANCEMENT AND RECORDING PROCEDURES EVALUATED, CONT'D
C. DIRECT PHOTOGRAPHIC ENLARGEMENT

METHODS

Direct enlargement of portion of original 70 mm positive transparency by a factor of 13 to achieve a negative print at a scale of 1:260,000. Instructions to photographer to expose for best visibility of sediment pattern in Grizzly Bay with secondary attention to the darker patterns in Carquinez Strait. MSS band 6 used. Three print exposures made.

Direct enlargement of portion of 70 mm negative transparency to achieve positive paper print. Same scale as (1) above. Negative was made by contact printing onto Eastman Commercial Duplicating film (slightly inferior to obtaining negatives from the EROS data center, but avoids the long turn-around time).

RESULTS

Undoubtedly the best hard copy results of this series. Probably would re-photograph fairly well onto movie film (assuming an adequate registration scheme). Sediment patterns are weak, but the excellent detail contrast for small features like bridges and the mothball fleet lend subjective confidence to the presentation.

Sediment plume structure noticeably less than for method (1) above. Visual contrast between gray steps 0 and 1 also less than for method 1. Bright land regions subjectively disturbing but not as much so as for direct viewing of the CRT displays (per methods A4 and B3). Overall effect roughly comparable to best photo prints obtained by photographing ESIAC screen (Method B1).

2

off the strip chart for intervals of approximately one hour. There is apparently a 2-3 fold change in turbidity which appears to be inversely proportional to specific conductance (salinity). The implications of this to remote sensing are that any photograph would only record an instantaneous event and coordinating with ground truth so that an identical sample (representing the image in both time and space) could be obtained would be difficult.

In addition to temporal variability there is a spatial variability. Figure 6 contains a smoothed curve for the turbidity track between two Suisun Bay stations on June 23, 1976. The data for this figure were obtained by continuously pumping water to the analyzer-recorder as the boat ran between stations. The resulting strip chart was too long to include directly in the report; therefore, values were picked off at a common time interval (approximately five minutes) and plotted. As expected, there was considerable spatial variation in turbidity, but not as much as was encountered in the tidal cycle study. Again, the problem of correlating ground truth with remote imagery is compounded by variability concerns.

Analysis of Satellite Imagery by Stanford Research Institute

The people from SRI concentrated their efforts on Suisun Bay, the area of particular interest to the Department of Water Resources. After receiving the images, they were ranked for utility (visibility of features of interest on a scale of 1 to 10). An example how such a ranking worked can be seen from Figure 7, image No. 2342-18091 taken on December 30, 1975. This appears to be representative of the more pronounced sediment patterns observed in Suisun Bay. The image was ranked for utility as 0, 1, 3, and 0 as viewed in bands 4, 5, 6, and 7 respectively.

Various enhancement and recording procedures employed are summarized in Table 2, along with the results of such procedures in terms of what type of images they produced. Some of the peculiarities resulting from the various positive/negative inversions may be clarified by reference to Figures 8 and 9. Figure 8 shows a simplified block diagram of the ESIAC video system. It shows that in addition to the choice of picture polarity determined by whether positive or negative film is used, switches A and B provide two places where the signal can be inverted electrically. If the non-linear amplifier is being operated in its linear mode (STRETCH and COMPRESS controls both set to zero), an electrical inversion at switch A can be completely cancelled by a second inversion at switch B, as far as the output displays are concerned.

On the other hand, a switch from positive to negative film cannot be completely compensated for merely by flipping either switch A or B. This is because of the logarithmic nature of the film exposure process during copying from negative to positive or vice versa. That is, during copying, film density differences between specified gray step levels are preserved (approximately), not the relative light transmission increments. In Figure 9 the result is indicated numerically for the standard Landsat 15-step tablet. Figure 9 shows that with the cameras scanning the gray step tablet portion of a positive transparency, the uninverted camera electrical output available, for example, at the positive pole of a switch A will be a descending linear staircase similar to curve A. With nothing else changed except for a switch from positive to negative film, the cameras output waveform will resemble curve B, a very non-linear rising staircase. This result can be derived from the light transmission data for the negative film given near the bottom

of the graph. An electrical inversion of this waveform either at switch A or switch B will result in the non-linear descending staircase shown as dotted curve C. Note that while the gross polarity is the same as for curve A; i.e., the blackest portion of the original scene generates a near-zero level video voltage and the brightest portions of the original scene generated a +1 volt video response in both cases, the emphasis given to intermediate steps along the gray scale table is insignificantly different. Normally, in careful TV practice one uses the non-linear amplifier to attempt to compensate for these curvature effects so that pictures derived from either positive or negative transparencies will appear identical on the output display. In this particular case the large amount of stretch given by the negative film to the interval between gray step zero and gray step one can be used advantageously since that is precisely the radiance region where much sediment plume information resides in the Landsat records. By employing this stratagem, low radiance scene information can be read into the cameras at high light levels, giving a clean signal and the uncompensated stretched signal makes better use of the available dynamic range in the disc recorded to yield an improved signal-to-noise ratio for the low radiance information.

Examination of curves A and C (or of equivalent real-life waveforms read from Landsat films) shows that this advantage of "free" black stretch by using negative transparencies ceases to be effective above about gray step two or three. For many scenes, sediment plume information may come in those radiance ranges, particularly in bands 4 and 5 with slight haze present. For those cases it is better to operate from positive transparencies.

The question then becomes, why was only little improvement noted in the December 30 image when operating from a negative transparency. Although the exact cause was not certain, it was probably tied in with the fact the display CRT and the film recording processes follow the waveforms graphed above and both processes are highly non-linear.

One study objective was to produce a time lapse movie showing the changes in sediment patterns during the 18-month period. After a considerable amount of effort was expended on this objective, Mr. William Evans (Staff Scientist, Atmospheric Sciences Laboratory, Stanford Research Institute) concluded that the use of ESIAC display to produce such a movie had a high probability of proving disappointing. The alternative of photographing direct enlargements in an animation stand, with registration, sequencing, and timing being done on ESIAC appeared promising, but beyond the scope of their budget. With this the time-lapse movie idea was dropped.

The people from Stanford Research Institute used ESIAC to produce horizontal reflectance profiles across selected scan lines in the Suisun Bay area (see Figure 10). All bands for several of the available Landsat images were scanned; however, in view of the rather uniform results obtained only a couple of examples are included in this report. Figure 11 illustrates the results of scan line F on September 30, 1975, Band 6. Also included is the reflectance values for a portion of the gray scale contained in the satellite imagery. The ticks on the scan line represent one kilometer distances on the water, and the water portion of the scan begins at about kilometer 0.5 and ends at about kilometer 5.5. As a point of interest, scan line F represents an area

of the Bay-Delta containing some of the greatest visual contrast on the available imagery.

The scan line is notable for the lack of detail in reflectance values. All the values are between steps 2 and 3 of the gray scale and the variability along the line is about the same as that encountered in the gray scale. In other words, much of the variability shown may have been due to the emulsion itself. This lack of detail is somewhat surprising because there is considerable detail visible in the photograph (see Figure 12). For comparison the U-2 infrared photograph (also taken on September 30, 1975) was scanned along scan line F, or as close as it could be approximated. This scan line is shown in Figure 13, along with a portion of the gray scale for the IR film. Again, there is little detail apparent in the reflectance diagram, although there is considerable in the photograph (Figure 14).

It is possible that what we saw in the reflectance profiles was not a limitation of the use of remotely sensed imagery, but perhaps some limitation of the use of ESIAC itself. It might be that the transfer of images to television format results in the loss of some subtle features, especially when these features are essentially being reproduced from third generation data. It did appear that the somewhat greater ultimate information content and precision inherent in digitally recorded Landsat records would not have significantly altered the results of this study, even if they had been available within the budget limitations.

One additional approach for data presentation was attempted, the so-called "contouragraph" data display. Contouragraph is a term occasionally applied to a method of displaying image-type data that combines some of the features of more conventional "A-scan" line radiance profiles and two-dimensional brightness modulated images. It is a relatively easily derived by-product when the source data already have been scanned in a rectangular raster format as in the case of the ESIAC closed-circuit television system, and for certain types of scene content provides a startling and occasionally useful three-dimensional effect that is a form of image enhancement.

To produce the display, a rectangular television-like raster composed of closely-spaced horizontal lines is first generated on a cathode ray tube screen. Then a small amount of Y-direction displacement is superimposed on each scan line, the amount being proportional to the brightness or radiance information associated with that scan line. This of course causes overlap into the territory normally occupied by the immediately preceding scan lines, but since the brightness patterns in the image normally have a high degree of spatial correlation, the effect is more like waves of hair than of an uncombed tangle. The scan line pileup near the peaks of the deflection modulation adds a brightness modulation component to the normally blank raster tends to enhance the three-dimensional effect and transform subtle brightness patterns into rolling hills at the same time localized bright spots are transformed into towering pinnacles. Occasionally the effect can be further enhanced by superimposing a small amount of normal Z-axis (brightness) modulation along each scan line in the usual

television format. Both Y-axis and Z-axis modulation were used in creating the reproduction of the Navy mothball fleet and surrounding sediment patterns in Suisun Bay as derived from as MSS-6 Landsat image (Figure 15).

CONCLUSIONS

In this section I list some of the conclusions reached during this study and a brief discussion of how each conclusion relates to the overall objective of evaluating the use of remote sensing to monitor surface water quality.

1. The amount of money allocated to this study was not sufficient to achieve the objectives outlined in the introduction to this report.
During the time between the formulation of the study and the awarding of the contract, costs escalated considerably but the contract amounts were not increased accordingly.
2. In a complex and dynamic system such as the San Francisco Bay and Delta the collection of adequate amounts ground truth data to support remote imagery must involve several boats in the water with crews simultaneously measuring several water quality parameters.
Spatial and temporal variations of the parameters of interest are so great that approaches other than synoptic (synchronized multi-point sampling) do not provide enough information to evaluate patterns observed in specific images.
3. In California, water quality conditions are improving as a result of the Porter-Cologne Water Quality Act, and provisions of PL 92-500.
This conclusion was reached after looking at images from the Bay-Delta and analysis of other water quality data collected throughout the State. The conclusion impacts the objectives of the study because present and future water quality problems are often of such a subtle nature that they can be detected by sophisticated chemical analysis and will not show up directly on remotely sensed images.

4. Stanford Research Institute's ESIAC (Electronic Satellite Image Analysis Console) equipment lacked the sensitivity to quantitatively define turbidity plumes which were apparent to the unaided eye. This problem arises because second and third generation images are being analyzed. In this case direct examination of photographic reproductions of Landsat images, perhaps with the aid of a film densitometer and a planimeter would have been the most effective analysis technique. The use of digital tapes would probably not have significantly improved ESIAC's capability for data analysis.
5. For most water quality monitoring applications Landsat imagery is too infrequent and of too small a scale to be useful in routine monitoring programs.
6. Imagery from U-2 and conventional aircraft can be effectively used monitor gross water quality changes. This conclusion is particularly relevant in California's drought year when waste discharge may be a significant portion of the flow in many streams.

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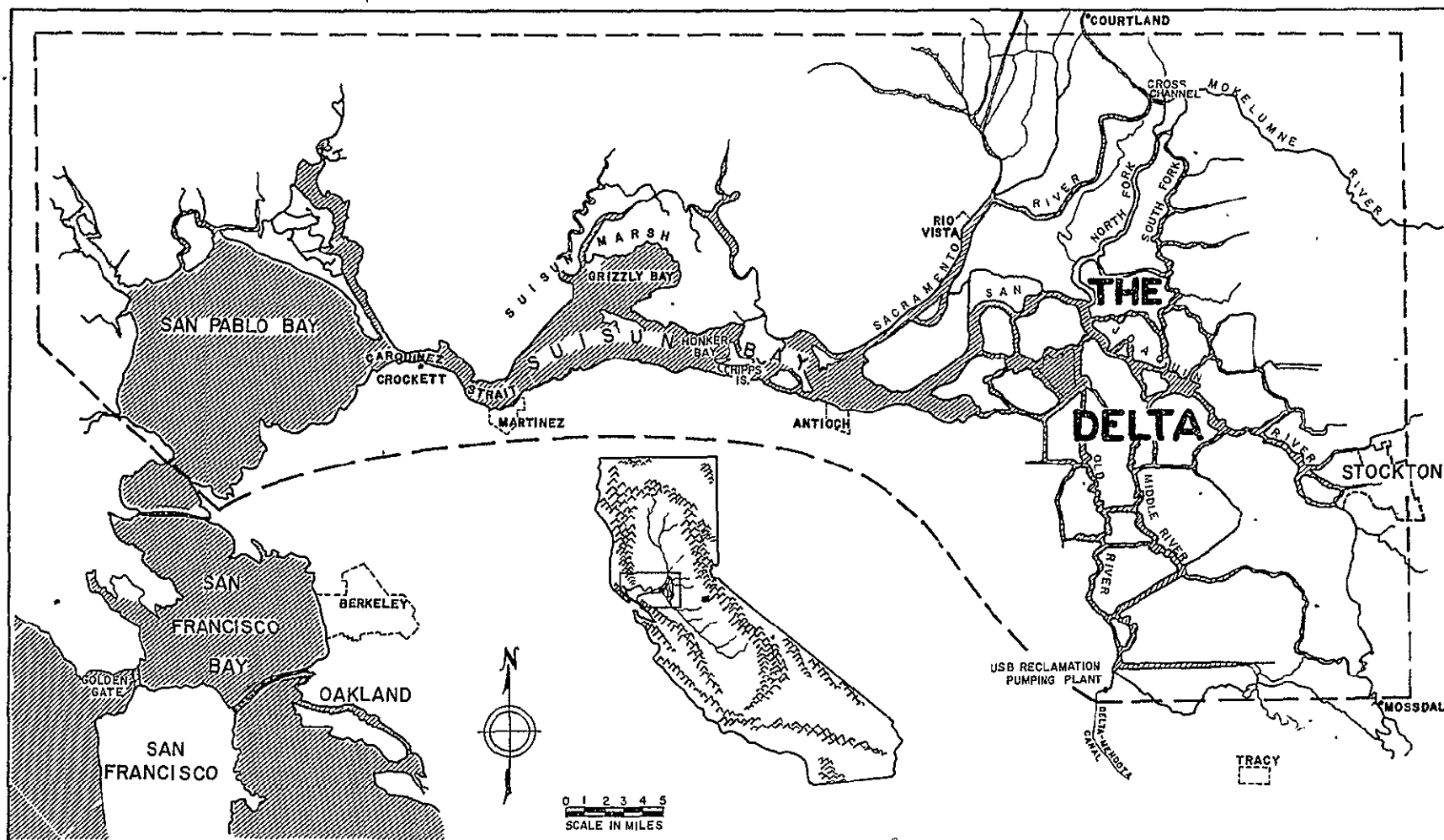


FIGURE 1 SAN FRANCISCO BAY AND DELTA ESTUARY

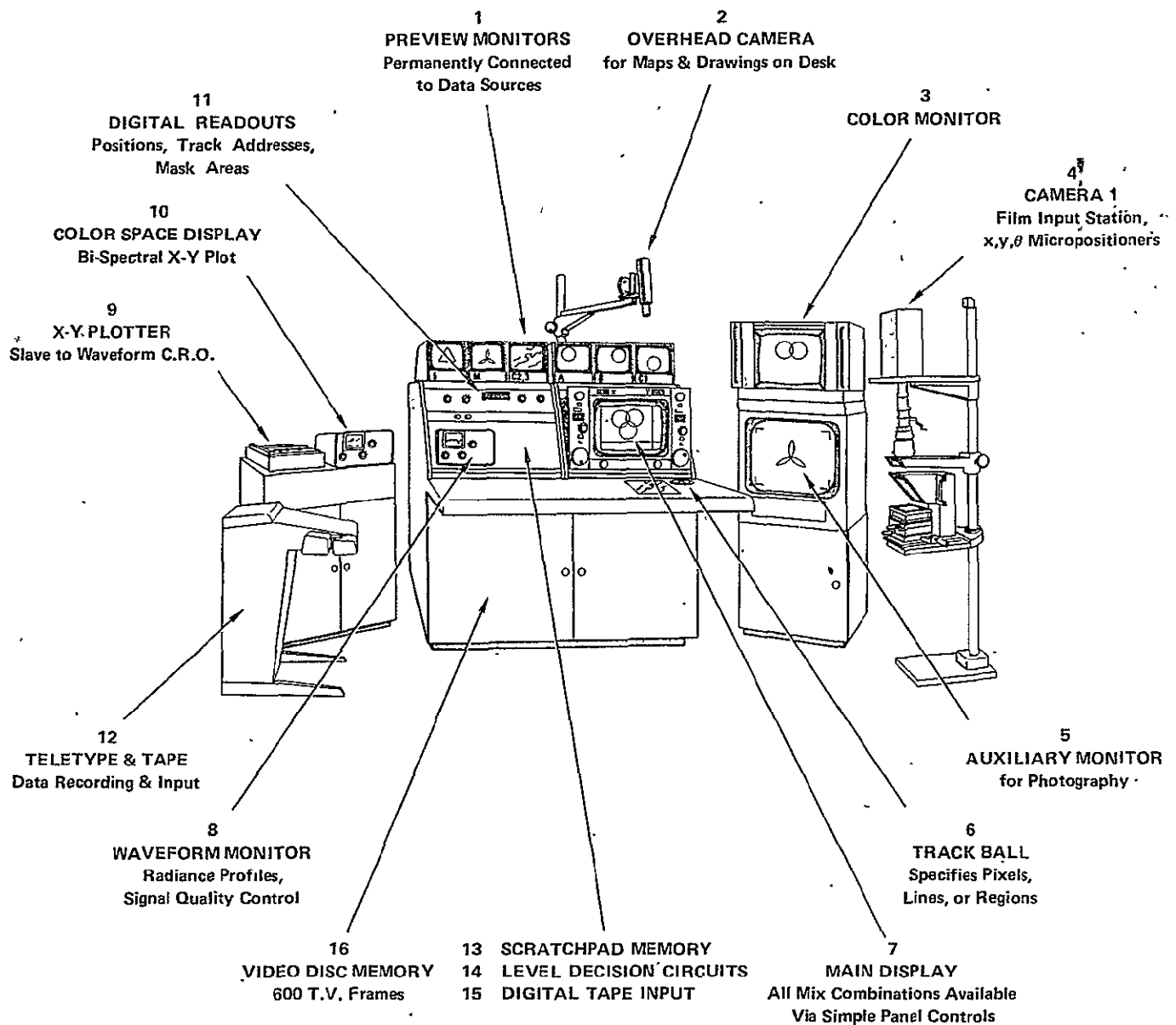


FIGURE 2.

PICTORAL DIAGRAM OF ELECTRONIC SATELLITE IMAGE ANALYSIS
CONSOLE (ESIAC)

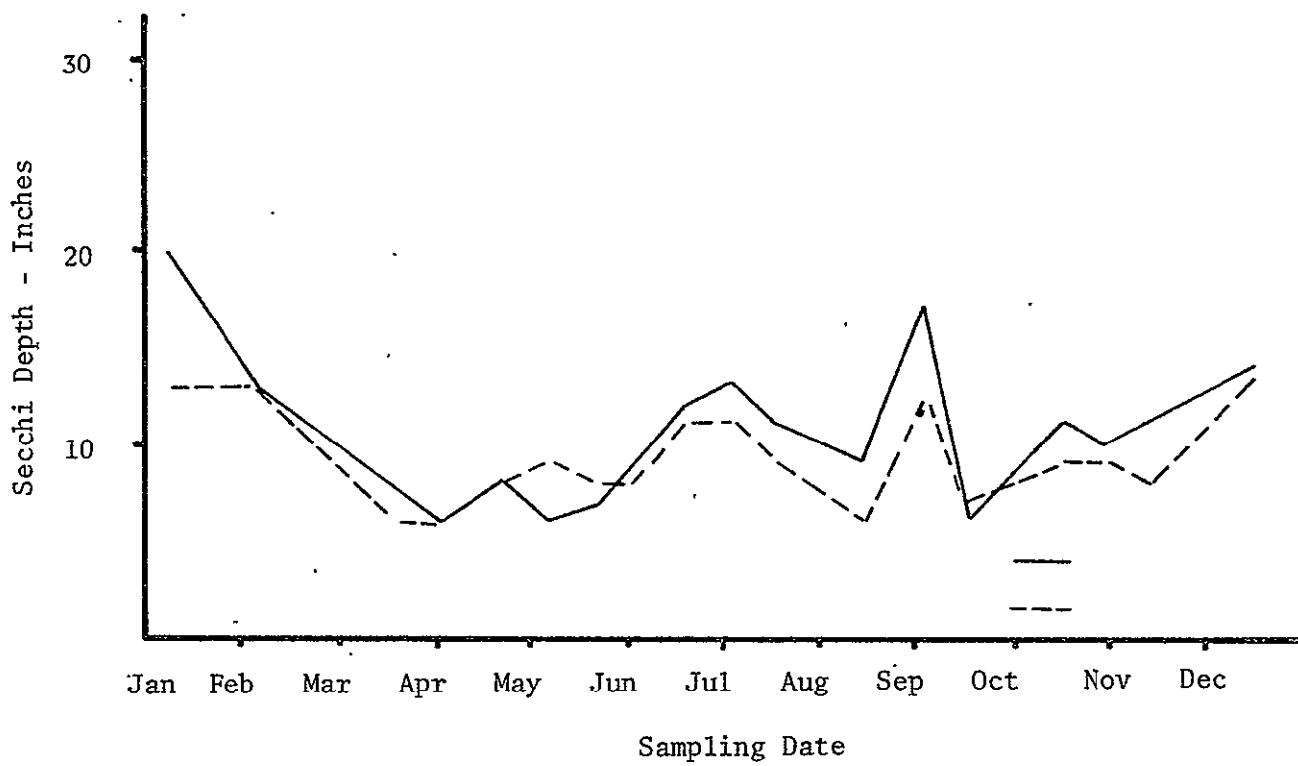


FIGURE 3.
VARIATION OF SECCHI DEPTH AT 2 DELTA STATIONS DURING 1976

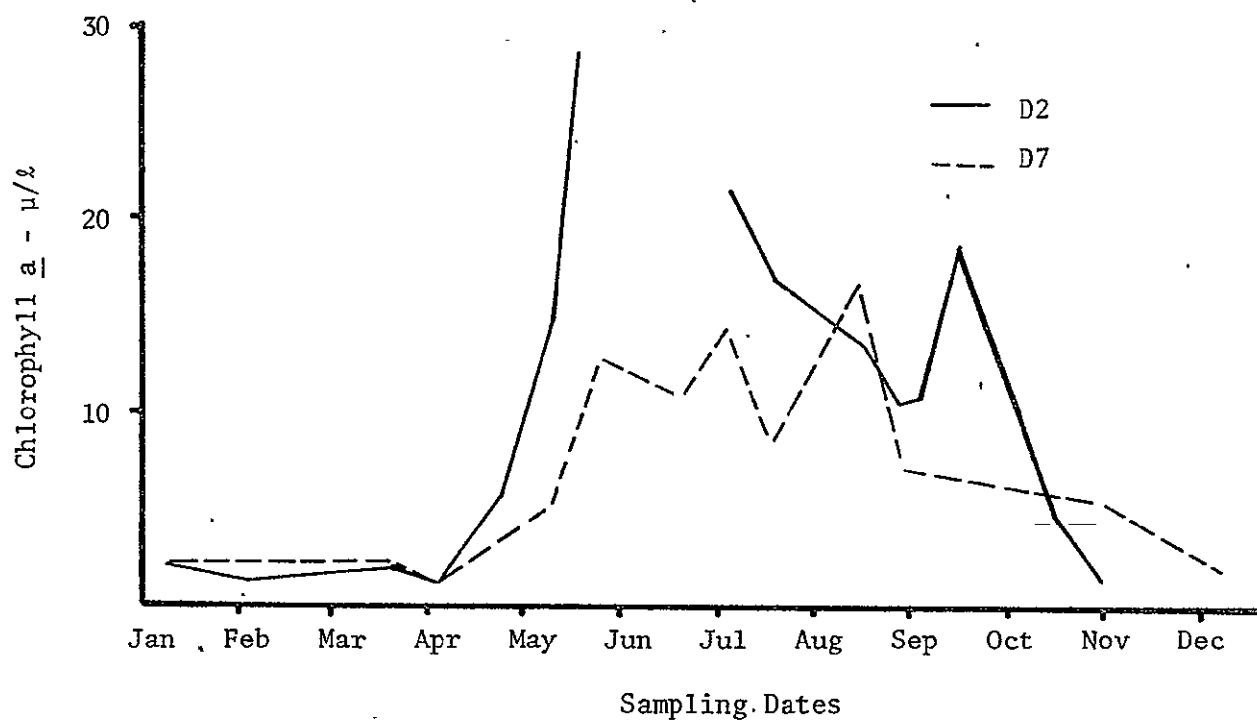


FIGURE 4.

VARIATION OF CHLOROPHYLL A (CORRECTED FOR PHEOPHYTIN) AT 2 DELTA STATIONS DURING 1976

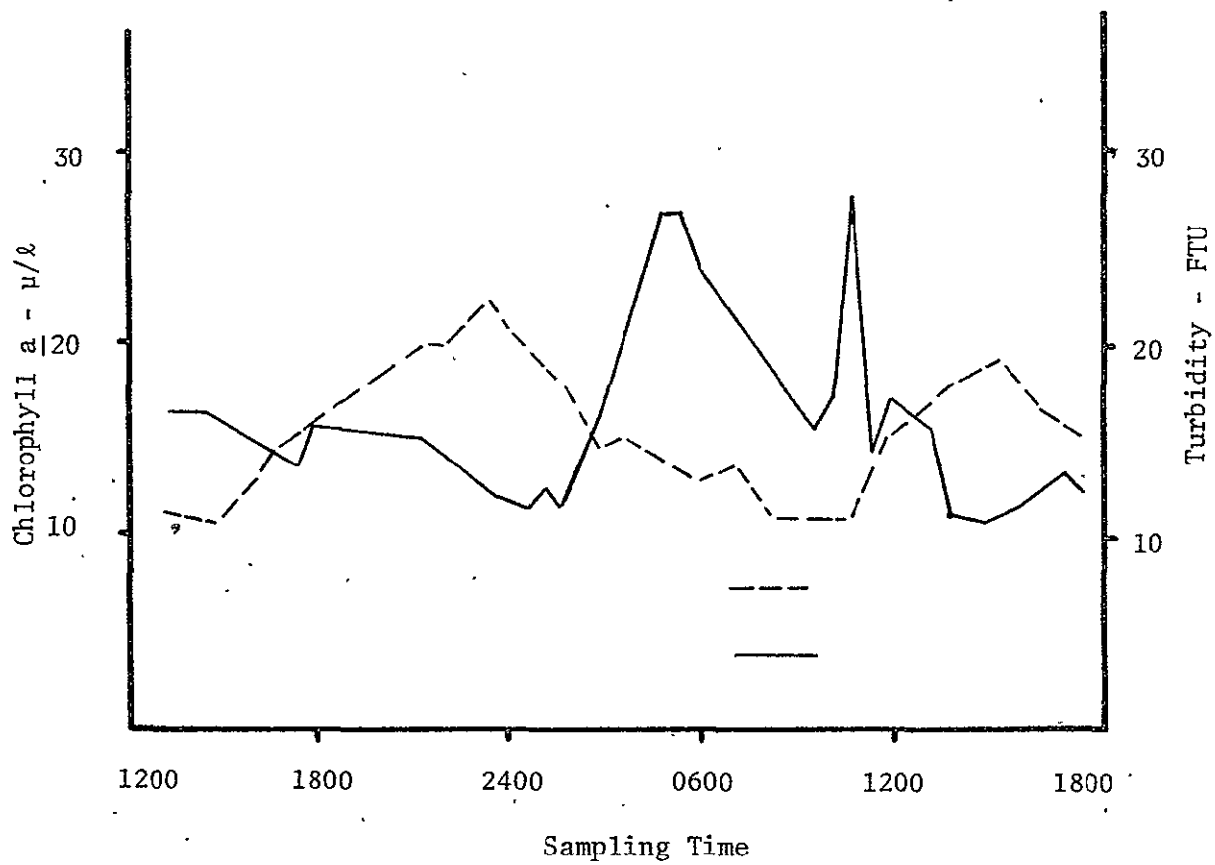


FIGURE 5.

DIEL FLUCTUATIONS OF TURBIDITY AND SPECIFIC CONDUCTANCE
AT STATION D2 ON 8-17/18-76 (SAMPLES FROM 1 METER DEPTH)

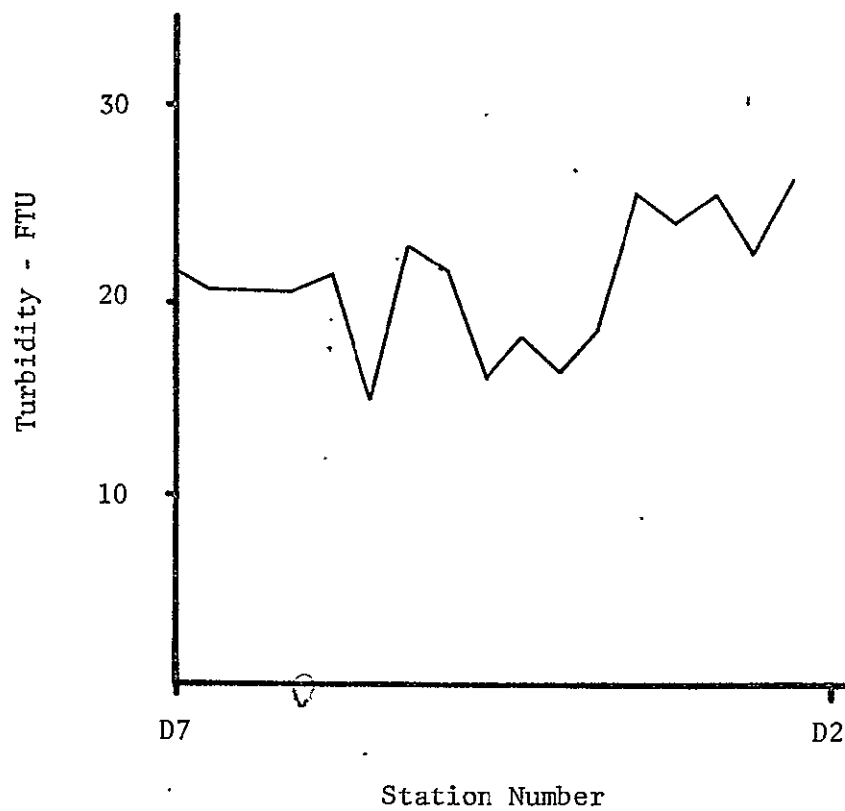


FIGURE 6.

TURBIDITY TRACK BETWEEN STATIONS D7 AND D2 ON 6-23-76
(SAMPLES FROM 1 METER DEPTH)

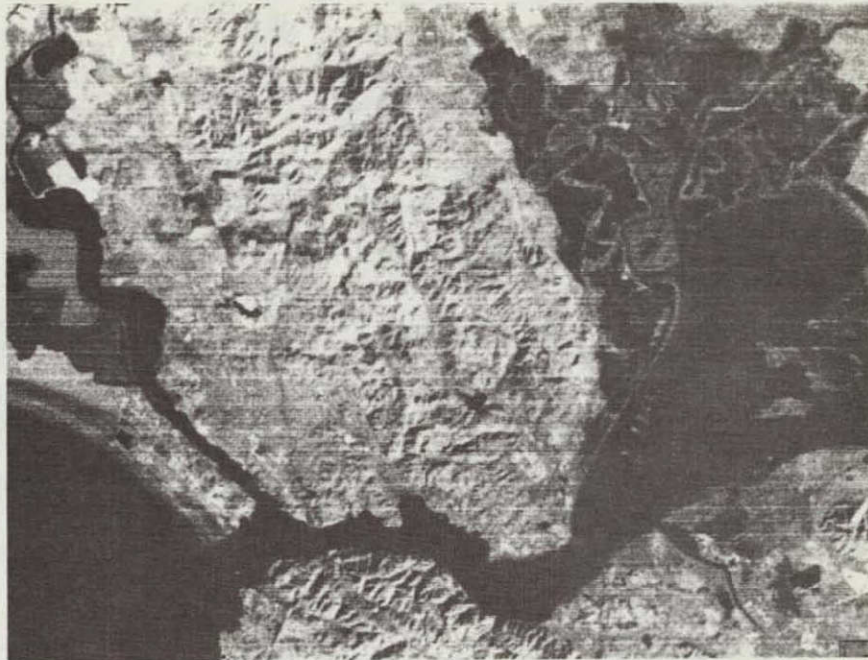


FIGURE 7. LANDSAT IMAGE 2342-18091, DECEMBER 30, 1976, BAND 6
RANKED FOR UTILITY. (SEE TEXT FOR EXPLANATION.)

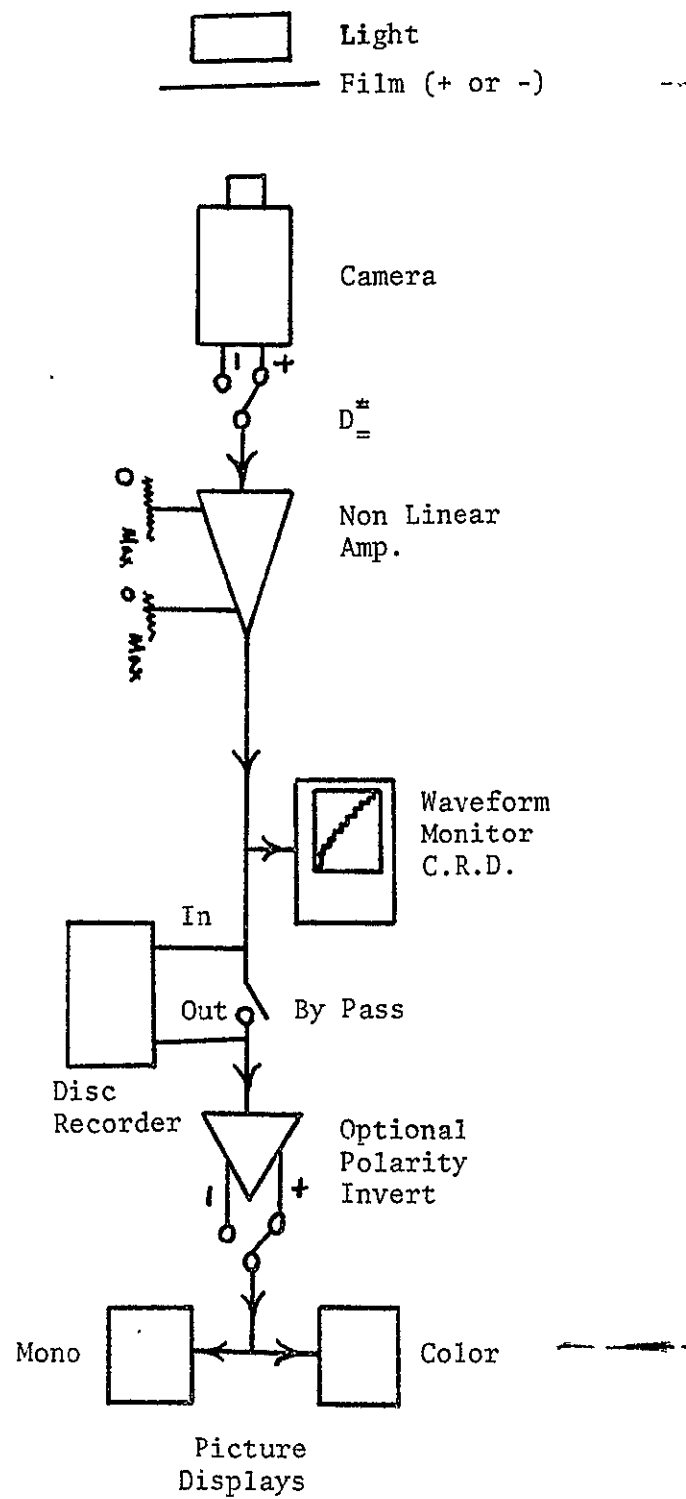


FIGURE 8. SIMPLIFIED BLOCK DIAGRAM OF ESAC

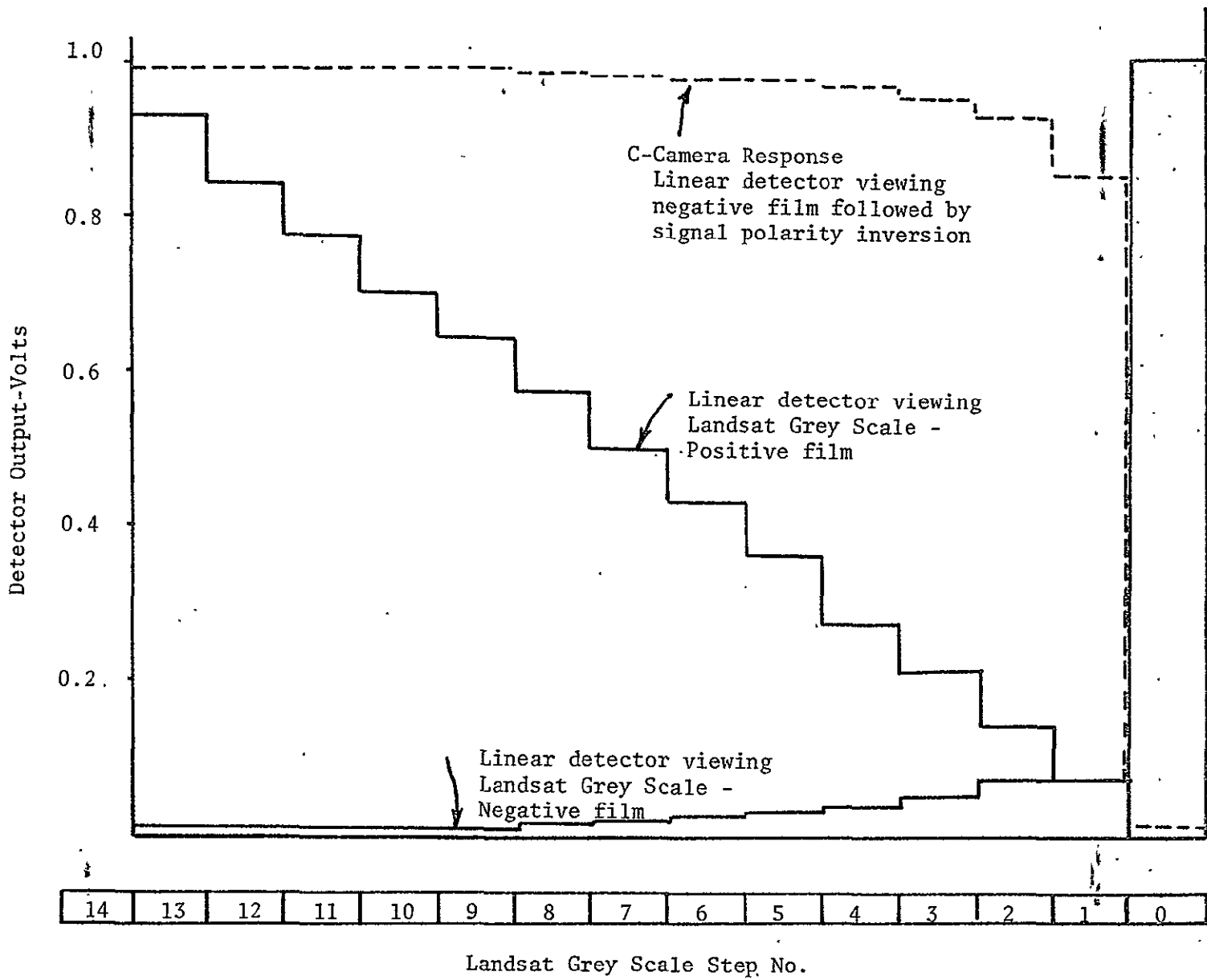


FIGURE 9. CAMERA RESPONSES TO LANDSAT GRAY SCALE STEP TABLET

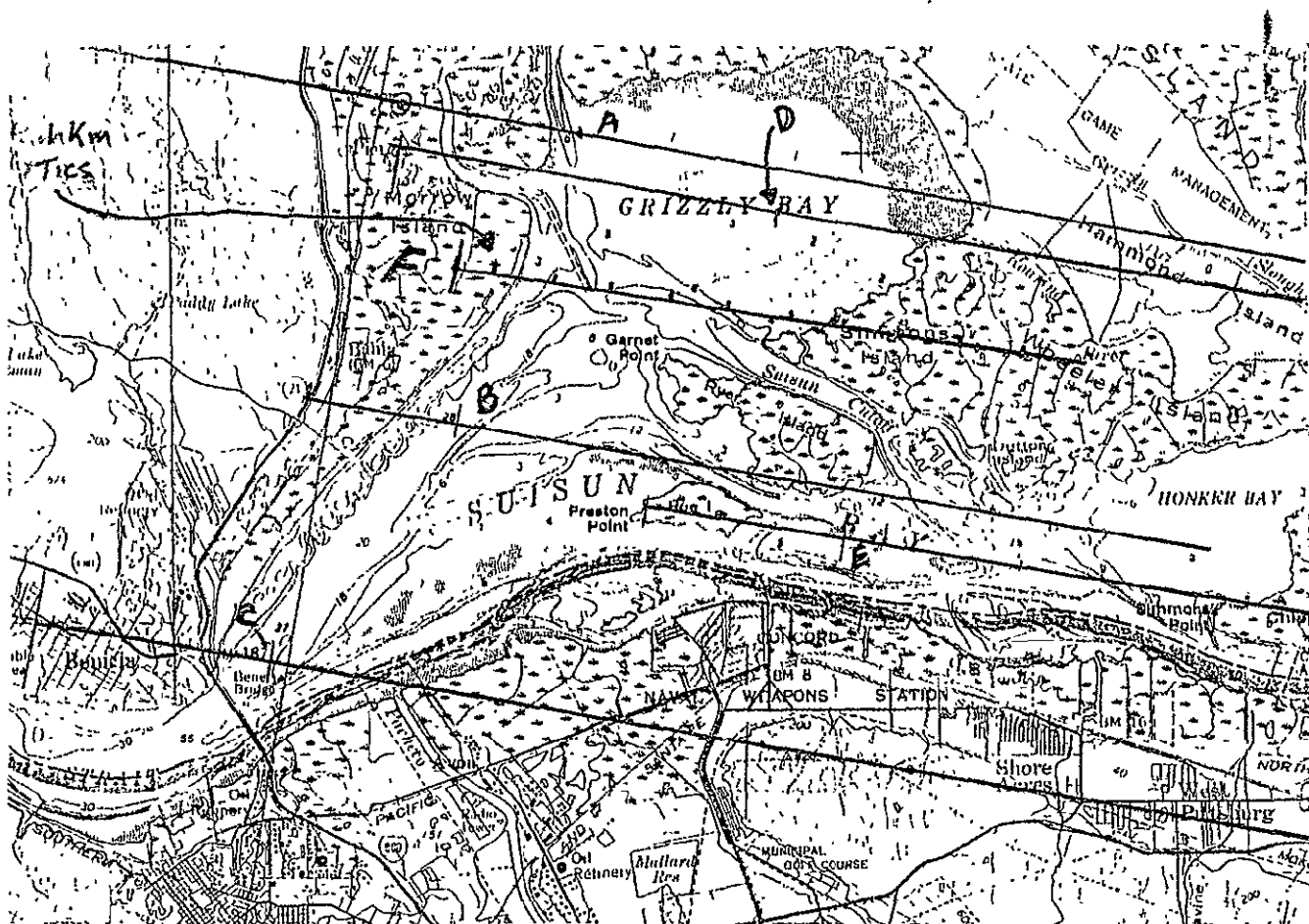


FIGURE 10.

LOCATION OF SCAN LINES ACROSS SUISUN AND GRIZZLY BAY

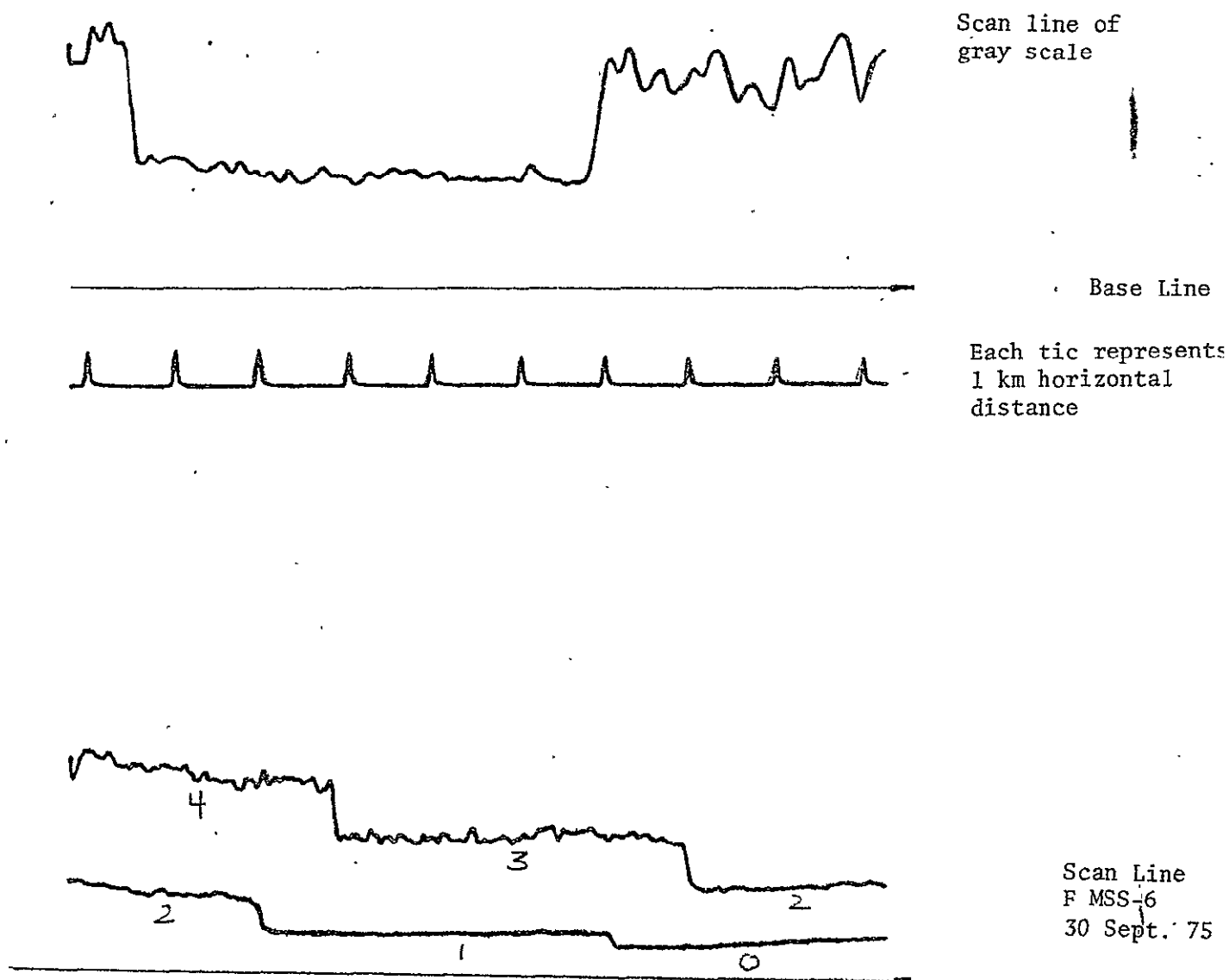


FIGURE 11.

REFLECTANCE VALUES FOR SCAN LINE F, SEPTEMBER 30, 1975,
LANDSAT BAND 6



FIGURE 12. LANDSAT IMAGE, SEPTEMBER 30, 1975, BAND 6

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

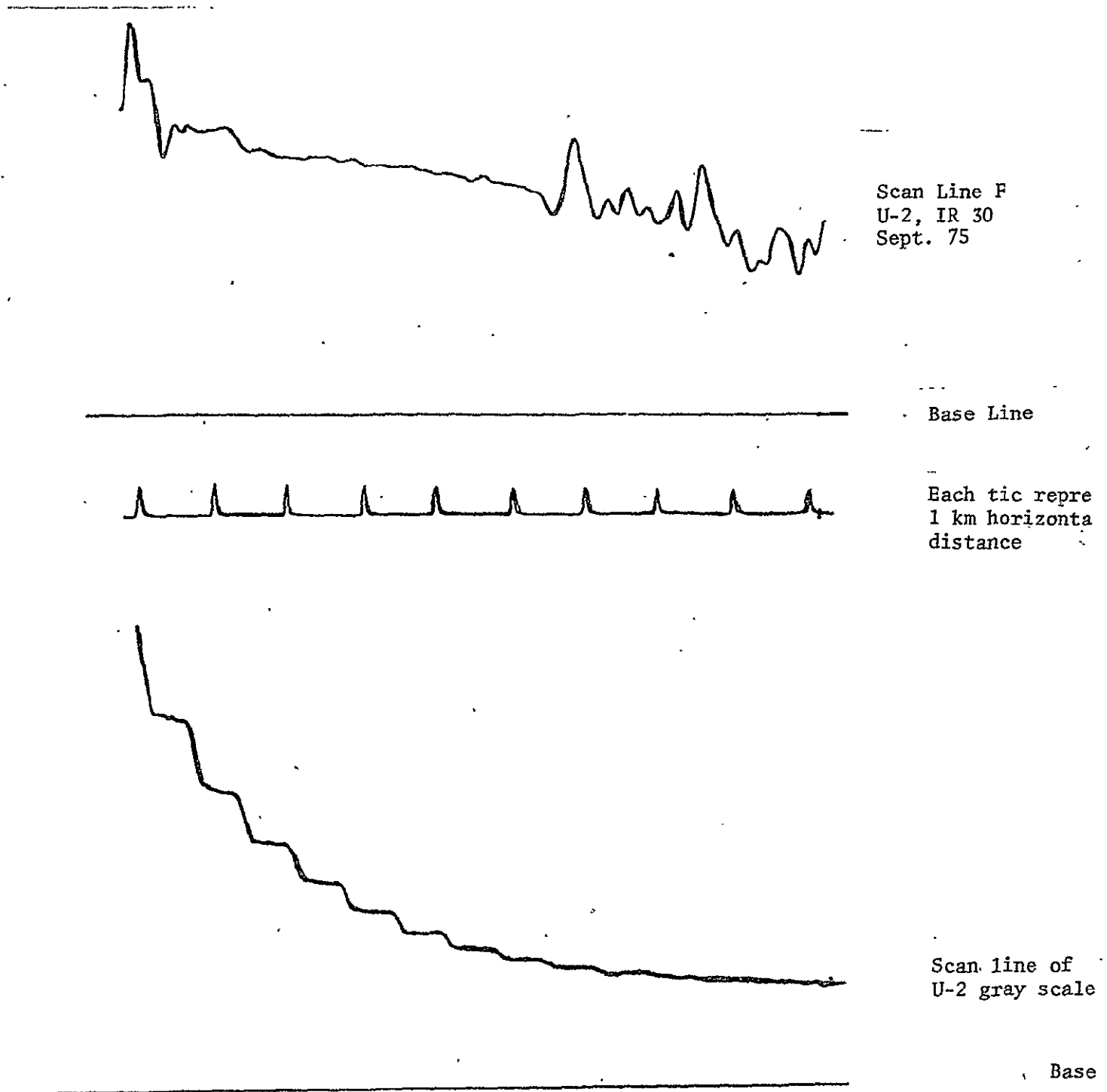


FIGURE 13.

REFLECTANCE VALUES FOR SCAN LINE F, 30 SEPTEMBER, 1975,
U-2 COLOR IR



FIGURE 14. U-2 IMAGE, 30 SEPTEMBER, 1975, COLOR IR

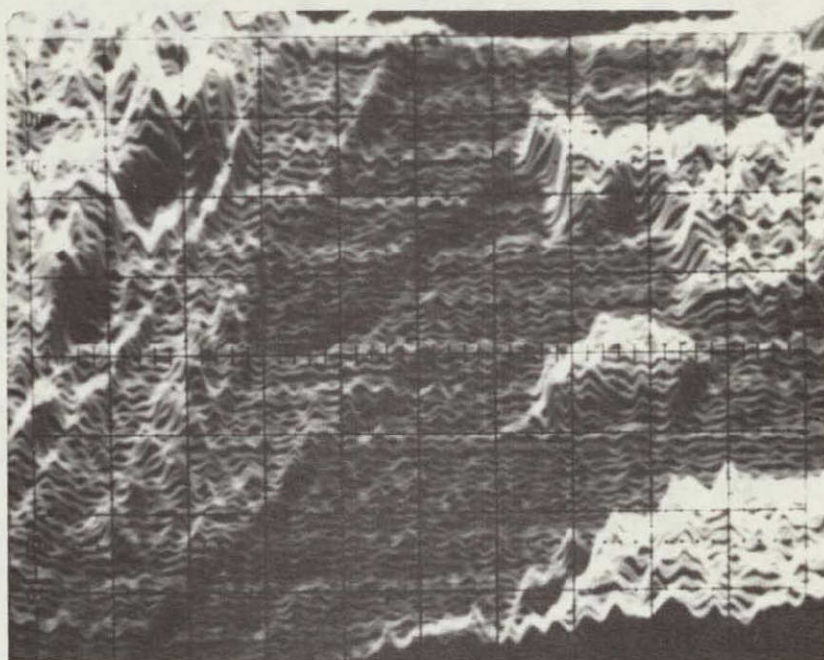


FIGURE 15. CONTOUROGRAPH DISPLAY, MSS BAND 6, LANDSAT IMAGE FROM 30 SEPTEMBER, 1975. PORTION OF GRIZZLY BAY. MOTHBALL FLEET IS AT LEFT OF PHOTOGRAPH.

